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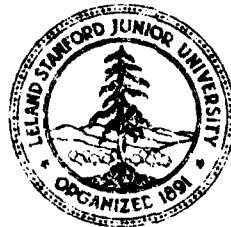Stanford University

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ENERGY RELEASE IN SOLAR FLARES

P. A. Sturrock, P. Kaufmann, R. L. Moore and D. F. Smith

Abstract

We examine observational evidence concerning energy release in solar flares. We propose that different processes may be operative on four different time scales: (a) on the sub-second time scale of "sub-bursts" which are a prominent feature of mm-wave microwave records; (b) on the few-seconds time scale of "elementary bursts" which are a prominent feature of hard X-ray records; (c) on the few-minutes time scale of the impulsive phase; and (d) on the tens-of-minutes or longer time scale of the gradual phase.

We propose that the concentration of magnetic field into "magnetic knots" at the photosphere has important consequences for the coronal magnetic-field structure such that the magnetic field in this region may be viewed as an array of "elementary flux tubes". The release of the free energy of one such tube may produce an elementary burst. The development of magnetic islands during this process may be responsible for the sub-bursts. The impulsive phase may be simply the composite effect of many elementary bursts.

We propose that the gradual phase of energy release, with which flares typically begin and with which many flares end, involves a steady process of reconnection, whereas the impulsive phase involves a more rapid stochastic process of reconnection which is a consequence of mode interaction.

In the case of two-ribbon flares, the late part of the gradual phase may be attributed to reconnection of a large current sheet which is being produced as a result of filament eruption. A similar process may be operative in smaller flares.

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1. Introduction

It has been realized for some time that magnetic reconnection plays an important role in solar flares. It was realized by Giovanelli (1947, 1948) that flares are essentially electromagnetic phenomena. Dungey (1958) pointed out that magnetic neutral points offer favorable sites for particle acceleration. Sweet (1958a,b) noted that such energy release may occur in entire current sheets. Gold and Hoyle (1960) proposed an alternative configuration with similar provision for the storage and release of magnetic energy.

In developing theories of solar flares, such as those referred to above, there has been a strong tendency to concentrate on the very sudden release of energy occurring during the "impulsive" phase, which is closely related to what has been called the "flash" phase or "expansion" phase in earlier work based primarily on H-alpha data. It was implicitly assumed that to explain the impulsive phase is to explain the complete flare.

The above viewpoint is no longer accepted. In the Skylab workshop on solar flares (Sturrock 1980), it was clearly recognized that most flares manifest release of energy during an "onset phase" (including what is termed "preheating") occurring before the impulsive phase. This energy is seen most clearly in the early buildup of soft X-ray emission. In this context, one should also recall that filament activity frequently occurs before a flare (Smith and Ramsey 1964); this activity may be regarded as a "precursor" if it occurs about an hour before the flare, or as part of the "onset phase" if it occurs only a few minutes before the impulsive phase. Although Kiepenheuer (1964) argued some time ago that filament activity and flares should be regarded as different aspects of one complex process, it is still usual to regard filament eruption and flares as separate but related phenomena (Van

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Hoven et al. 1980). A gradual onset phase preceding the impulsive phase can also occur in flares having no visible filament eruption; an especially well observed example is the flare of 1980 November 1, studied by Tandberg-Hanssen et al. (1983).

Although radiation continues long after the impulsive phase, this long-lived radiation may often be interpreted as the slow decay of energy suddenly released during the impulsive phase. For instance, the soft X-ray emission can be attributed to hot plasma formed by "evaporation" of gas from the chromosphere during the impulsive phase (Neupert 1968; Hudson and Ohki 1972; Hirayama 1974; Antiochos and Sturrock 1976). However, careful analysis has shown that, for some flares at least (Datlowe et al. 1975; Moore et al. 1980), there must be continued energy release in what has been termed the "late phase" of a flare (Sturrock 1980). Indeed, H-alpha data for "two-ribbon" flares (Svestka 1976) provide very strong evidence for such continued energy release. In this case, the two flare ribbons drift slowly apart (receding from the magnetic neutral line) so that, late in a flare, regions of the chromosphere are being heated which were not heated during the impulsive phase.

Substantially the same conclusion has been reached by Kundu (1965) in his analysis of flare-related radio emission. He finds that this emission occurs with two distinct phases, which he terms "impulsive" and "post-burst," demonstrating that radio emission requires continued energy release after the impulsive phase of a flare. The division of microwave bursts into two broad classes of "impulsive" and "gradual" was indeed proposed even earlier by Covington and Harvey (1958).

The facts listed above led, in 1980, to the view that there are not one but three phases of energy release in solar flares (Sturrock 1980), namely, the onset phase, the impulsive phase, and the gradual phase. Feldman et al.

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(1982) have argued from their analysis of the hard and soft X-ray emission of two M-flares (Doschek et al. 1981) that, for these flares at least, the onset phase and the late phase form a single continuous sequence, distinct from the impulsive phase. However, for most two-ribbon flares, the H-alpha morphologies and time-curves of the onset phase and late phase are quite different, indicating that we should not generalize the argument of Feldman et al. into the proposal that for all flares, the onset phase and the late phase are simply two stages of a single process.

Kane (1974), some time ago, introduced the term "gradual phase" to characterize the phase of soft X-ray emission which follows the impulsive phase of a flare. We propose that the onset phase and the late phase of energy release may both be termed the "gradual" phases of energy release, to distinguish them from the impulsive phase.

It appears to us that there are at least two distinct modes of energy release in a typical solar flare. One mode is responsible for the impulsive phase, and another for the two gradual phases. In terms of the usual assumption that energy release in solar flares is due to the release of free energy associated with current-carrying magnetic-field configurations, the two modes may, for instance, represent modes of reconnection, or reconnection in different types of magnetic-field configurations. These possibilities will be discussed further in subsequent sections.

In seeking to identify the number and characteristics of the various modes of energy release involved in flares, it is an oversimplification to consider only two modes associated with the impulsive and gradual phases. It is generally believed that the primary energy release process produces high-energy electrons (and sometimes relativistic electrons and ions); the most direct indicators of these high-energy electrons, hard X-ray emission and

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microwave emission, are produced by bremsstrahlung and *gyro-synchrotron* radiation, respectively. Recent observations indicate that time curves for these radiations contain a great deal of fine structure, which seems to require similar structure in the energy-release process.

Analysis of the hard X-ray emission from flares (Frost 1969; van Beek et al. 1974; de Jager et al. 1976) shows that the impulsive phase of a flare is typically comprised of a large number of events of comparatively short duration. The similarity in shape of the individual spikes in the X-ray flux led van Beek et al. (1974) to introduce the term "elementary flare burst" (which we abbreviate to "elementary burst") to characterize the process responsible for each such spike. The time scale of each such burst is in the range 5-20 s, and it was estimated that each such burst requires a total energy in the range $10^{27} - 10^{29}$ ergs.

From their analysis of millimeter-wave radiation, Kaufmann et al. (1980) claim that there is evidence for "quasi-quantization" of energy release in solar flares. The rapid variations in the millimeter-wave radio flux is interpreted as being caused by the superposition of a sequence of individual bursts, which we here term, for convenience, "sub-bursts". It is not possible to determine the time scale of each such burst, since they are usually "piled up". The most rapid rises ever observed have time scales of order 50 msec. Kiplinger et al. (1983) have reported that the hard X-ray flux from flares, as detected by experiments on board the SMM spacecraft, sometimes exhibits fluctuations on a comparable time scale.

More recently, Takakura et al. (1983) have made a comparative study of microwave and hard X-ray fluxes. It was found that "(a) on time scales of several seconds, the time structures are poorly correlated at different microwave frequencies and between microwaves and hard X-rays; (b) on sub-second time scales, however, the more rapidly repeating time structures are

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well correlated at two different microwave frequencies and between microwaves and hard X-rays." Tandberg-Hanssen et al. (1983) also found a lack of correlation between microwave and X-ray burst structures on time scales of several seconds. One intense spike-like burst observed at microwaves and hard X-rays, with half-power duration of about 5 s, was shown to be composed of a "slow" component with a time-scale of about 1 s and to display, at its peak, a repeating microwave subsecond structure with a time-scale of about 30-60 ms (Kaufmann et al., 1984).

On reviewing the above facts, we see evidence for at least three different "modes" of energy release, as characterized by different time scales and, to some extent, by different energy scales:-

(a) A mode of release with sub-second time scale, which is strongly evident in microwave radiation but is evident also in hard X-ray radiation, which we term "sub-bursts".

(b) A mode of energy release with a time scale of seconds, strongly evident in hard X-ray data, responsible for "elementary bursts".

(c) A "gradual mode." Analysis of the long-lived soft X-ray emission and of the evolution of H-alpha emission in large two-ribbon flares shows that, in some flares at least, there must be a mode of energy release with a time scale ranging from minutes (during the onset phase) to many minutes (during the late phase).

The "impulsive phase," which has a time scale of order one minute, may be regarded as a sequence of elementary energy releases corresponding to modes (a) and (b).

It has been realized for some time that many flares are closely related to the activation and eruption of filaments. Kiepenheuer (1964) wrote, "Those who have seen in an accelerated movie the brightening of a flare out of a dark

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filament, and the almost chaotic interaction of bright and dark structures, will not doubt the existence of a causal relation between the activation of a dark filament and the formation of a flare." The usual view is that filament activation somehow creates a magnetic-field configuration which then produces the flare (Svestka 1976). However, it is also possible that the association is even closer and that filament activation is to be regarded as an essential part of the flare process. Moore et al. (1983) have found good evidence for this viewpoint in an impulsive filament-eruption flare. Moreover, Zirin (1982) has expressed the opinion that all flares (even very small ones) involve the eruption of a dark feature.

We shall discuss energy release during the impulsive phase in Section 2, energy release during the gradual phase (comprising the onset and late phases) in Section 3, and make further comments on the overall problem in Section 4.

2. Impulsive Phase

As we have pointed out in Section 1, there are at least three ranges of time scales involved in the impulsive phase. The phase itself lasts for one minute to a few minutes. Hard X-ray emission exhibits a great deal of fine structure with time scales as short as 30 msec; however, the typical time scale for "elementary bursts" is in the range 5-20 s (van Beek et al. 1974). High-sensitivity millimeter-wave microwave data show a great deal of fine structure in the time variation, typically extending to fluctuations in the sub-second range. The analysis of some data of sufficient sensitivity indicates that the sub-second time structure appears also in the hard X-ray emission.

It is convenient to begin by considering the elementary X-ray bursts. There appear to be two ways to interpret this fine structure:-

(a) in terms of the time development of the reconnection process of an

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extended magnetic-field configuration; or

(b) in terms of reconnection of discrete small magnetic-field structures.

We shall discuss later in this section the possible role of fluctuations in the reconnection process. At this time, we note that there are reasons for exploring the possibility that the magnetic field of active regions has a cell-like structure which could lead to a pulse-like structure in the time development of energy release.

In recent years, we have learned that the early magnetograms have been misleading in indicating a continuous sequence of magnetic field strengths from the smallest detectable values (a few gauss) to the values characteristic of sunspot umbrae (several thousand gauss). Observations now indicate that, at the photospheric level, magnetic field lines tend to be pulled together into small flux regions with dimensions of order 500 km or less, in which the magnetic field strength is of order 1000 - 1500 gauss (Sheeley 1981). In consequence, the magnetic field at the photosphere tends to be aggregated into "knots" in which the flux has values of order $10^{18.4}$ Mx. There is insufficient data to determine the range of values of magnetic flux in such knots. For simplicity, we adopt the value $10^{18.4}$ Mx, recognizing that this is an arbitrary value in a range of likely values. This leads to the picture, which is undoubtedly oversimplified, that the magnetic field penetrating the photosphere is "quantized" in flux. This suggests that the magnetic field in the corona will comprise an assembly of flux tubes, which could be termed "elementary flux tubes", each originating in a strong-field knot in the photosphere and terminating in another knot. In general, one must expect each knot to be connected to more than one such tube. If this is the case, the magnetic flux of these tubes will normally be less than that of a typical

knot, but should have the same order of magnitude. (See Figure 1.)

If the magnetic field of the photosphere were structured as indicated above, the magnetic field at coronal heights will show little evidence of this structure if the magnetic field is current-free. The effect of the elementary-flux-tube structure would decay with height in a distance comparable with the distance between flux tubes. If the average photospheric field strength in an active region were 100 gauss, this inter-knot distance would be about 1500 km.

However, as has been pointed out elsewhere in connection with the problem of coronal heating (Sturrock and Uchida 1981), one must expect that granular motion of the photosphere will produce random rotations in these elementary flux tubes. Such rotation will lead to a distributed current in each such tube, in the form of a force-free field. It will also lead to intense current sheets separating contiguous tubes.

The free energy U (erg) stored in a single flux tube may be estimated from calculations presented by Sturrock and Uchida (1981):

$$U = \frac{\Phi^2 (\Delta\chi)^2}{16\pi^2 L} \quad , \tag{2.1}$$

where Φ (Mx) is the magnetic flux, L (cm) is its length, and $\Delta\chi$ (radian) is the angle of relative rotation of the ends of the tube.[2] The permissible range of values of $\Delta\chi$ will be limited by the requirement of MHD stability of the flux tube. A relevant analysis of the stability of force-free magnetic-field configurations has been made by Anzer (1968). If we apply his analysis to the simple Gold-Hoyle (1960) model of a force-free flux tube, of which the Sturrock-Uchida (1981) model is a simple extension, we find that the limit of MHD stability corresponds to $\Delta\chi = 2\pi$. On adopting this value as determining

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[2]Note that we choose to regard U, etc., as numbers. Thus U is the number of ergs of energy. The energy is U x (1 erg).

the maximum free energy which can be stored in such a flux tube, and on adopting the value $\Phi = 10^{18.4}$, we find that

$$U = 10^{36.2} \, L^{-1} \quad . \tag{2.2}$$

We see that a reasonable range of lengths $L = 10^8 - 10^{9.5}$ for the region responsible for the impulsive phase of a solar flare leads to the range $U = 10^{26.5} - 10^{28}$. This agrees fairly well, but not perfectly, with the estimate $10^{27} - 10^{29}$ erg for the energy associated with elementary bursts (van Beek et al. 1974).

The time scale for release of energy of a twisted elementary flux tube by means of reconnection does not admit of such a simple estimate. The shortest time in which the energy can be released is the time it would take a complete flux tube to unwind, given by

$$\tau_u = \int \frac{ds}{v_A} \quad . \tag{2.3}$$

For a fully ionized plasma in which the magnetic field strength is B and the density of electrons and ions is n (cm^{-3}),

$$v_A = 10^{11.3} \, B \, n^{-1/2} \quad . \tag{2.4}$$

It is clear that the largest contribution to the integral (2.3) comes from the extended weak-field region of the tube, not from the small, strong-field region near the footpoints. Hence, we may estimate τ_u in order of magnitude from

$$\tau_u = 10^{-11.3} \, L \, B^{-1} \, n^{1/2} \quad . \tag{2.5}$$

In the compact part of a solar flare responsible for the impulsive phase, it is likely that B is of order 10^2 or a little more, and that n (the preflare

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coronal electron density) is of order $10^{9.5}$, so that

$$\tau_u \simeq 10^{-8.5} \, L \quad . \qquad\qquad (2.6)$$

Hence, for L in the range 10^9 to $10^{9.5}$, we obtain estimates τ_u of order 2 – 10 s. This estimate agrees favorably with the typical duration of elementary bursts.

We now consider briefly the impulsive phase as a whole, and ask if it is possible to understand the time scale and energy scale in terms of the sequential energy release of the free-energy of a large number of elementary flux tubes. If reconnection in one flux tube triggers reconnection in an adjacent flux tube, then the disturbance will propagate transverse to the magnetic field with the transverse velocity given, in order of magnitude, by

$$v_\perp = R \, \tau_u^{-1} \quad , \qquad\qquad (2.7)$$

where R is the radius of the flux tube, and τ_u is the "unwinding" time for a single tube given by Equation (2.5). Then the time scale of the impulsive phase is given, in order of magnitude, by

$$\tau_I = L v_\perp^{-1} \quad . \qquad\qquad (2.8)$$

On using Equation (2.5) and noting that

$$R^2 B = \Phi = 10^{18.4} \quad , \qquad\qquad (2.9)$$

we obtain

$$\tau_I = 10^{-20.5} \, L^2 \, B^{-1/2} \, n^{1/2} \quad . \qquad\qquad (2.10)$$

If, for instance, we adopt typical values $B = 10^2$, $n = 10^{9.5}$, we find that τ_I will range from 20 s to 3 m as L varies over the range $10^9 - 10^{9.5}$ If $B = 10^2$

and L is appreciably less than 10^9, the number of flux tubes is very small. The impulsive phase, even of a large flare, does not involve dimensions much larger than $10^{9.5}$. This range of estimates of the duration of the impulsive phase is in reasonable agreement with observational data.

We now consider the total energy released during the impulsive phase, considering only the aggregate of the free energy of the individual flux tubes. Since N, the number of flux tubes, is given by

$$N = 10^{-18.4} \; B \; L^2 \quad , \tag{2.11}$$

and the maximum energy of an individual tube is given by (2.2), the total free energy of the assembly of flux tubes is given by

$$U_{FT} = 10^{17.8} \; B \; L \quad . \tag{2.12}$$

Note that this varies with average field strength and length scale in a way which differs significantly from that of the total magnetic energy, given approximately by

$$U_M = 10^{-1.4} \; B^2 \; L^3 \quad . \tag{2.13}$$

We find from the above equations that, if N is not too small,

$$U_{FT} = 10^{0.8} \; N^{-1} \; U_M \quad . \tag{2.14}$$

Hence, for a large flare, the amount of energy released during the impulsive phase may be only a small fraction of the total energy in the magnetic field—even of the total free energy of the magnetic field.

The above result tends to agree with the detailed analysis of the flare of 1973 September 5, made by Canfield et al. (1980) and Webb et al. (1980). For that flare, the total energy released during the impulsive phase was about $10^{29.3}$ erg whereas the total energy budget (mainly in mechanical energy) was

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in excess of $10^{31.3}$ erg. Canfield et al. (1980) estimate the area of H-alpha emission at $10^{18.5}$ cm^2. If we adopt L = $10^{9.2}$, the energy of the impulsive phase can be understood if the average field strength was $10^{2.3}$ gauss.

If we are to attribute the mechanical energy to magnetic free energy released during the flare, the total magnetic energy must exceed $10^{31.3}$ erg, perhaps by a factor of 10. This energy must therefore be derived from a field configuration which is stronger than $10^{2.3}$ gauss, or larger than $10^{9.2}$ cm, or both. This is not unreasonable, since the active region involved spots where the magnetic field strength would have been much larger than $10^{2.3}$ gauss.

According to Kaufmann et al. (1980), detailed analysis of millimeter-wave solar bursts is indicative of a "quasi-quantization" of this radiation. It has been found that impulsive millimeter-wave solar bursts typically consist of a sequence of narrow spikes. They overlap each other, and only the peaks of the spikes are observed. For bursts examined in detail, the shortest time difference between two individual spikes is in the range 30 ms to 60 ms (Kaufmann et al., 1984). The time scale of an individual spike emission, however, may well be larger than the inverse of the repetition rate. The flux level of bursts rises as the repetition rate of spikes increases, following an approximately linear relationship. It is this relationship which led Kaufmann et al. (1980) to propose that "the flare energetic injections are quasi-quantized in energy." The analysis of this data is complicated by the "piling-up" of data, an effect which has been analyzed recently by Loran et al. 1984).

The ratio of the mean radio flux to the mean repetition rate was found to be about 5 sfu sec at 22 gHz. If the length of a typical pulse is taken to be 10^{-1} sec, then the mean flux of an average pulse will be 50 sfu at the earth, which converts to angular flux density of radiated energy per unit bandwidth

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J_ν (erg Hz^{-1} s^{-1} sterad^{-1}) of $10^{9.1}$.

In order to interpret the microwave data, we use formulas for synchrotron emissivity from mildly relativistic particles developed by Petrosian (1981). We consider four cases: (a) δ = 3, B = 10^2; (b) δ = 3, B = 10^3; (c) δ = 5, B = 10^2; (d) δ = 5, B = 10^3; where $-\delta$ is the power-law index of the electron spectrum, yielding $-\frac{1}{2}(\delta - 1)$ for the power-law index of the radio spectrum. We consider, for simplicity, radiation perpendicular to the magnetic field so that $\theta = \pi/2$ in Petrosian's formulas. Then Equation (P.35a) [Equation (35.a) of Petrosian (1981)] yields

$$\gamma_0^2 - 1 = \frac{4\nu}{3\nu_g (1 + \delta)} , \tag{2.15}$$

where ν_g is the gyrofrequency, ν is the observed frequency, and γ_0 indicates the range of γ which gives the dominant contribution to the radiation. For the observed frequency $\nu = 10^{10.4}$, we find: (a) γ_0 = 5.1; (b) γ_0 = 1.9; (c) γ_0 = 4.3; (d) γ_0 = 1.7.

The quantity Z^{2m}, defined by (P.10), is given approximately by

$$Z^{2m} = e^{(-1/2)(\delta + 1)} , \tag{2.16}$$

from which we see that (a,b) Z^{2m} = 0.14; (c,d) Z^{2m} = 0.050. We note also, from (P.33), that

$$X = (1 + \delta)^{-1/2} , \tag{2.17}$$

so that (a,b) X = 0.50; (c,d) X = 0.41.

If the total number of electrons dN with γ in the range γ to $\gamma + d_\gamma$ is expressed as

$$dN = f(\gamma) \, d_\gamma , \tag{2.18}$$

we may use (P.11) to relate the angular flux density J_ν to $f(\gamma)$,

$$J_\nu = \frac{e^2}{c} \nu_b^{1/2} \nu^{1/2} f(\gamma_0) z^{2m} x_J . \qquad (2.19)$$

We have simplified Equation (P.11) by considering only the case $\Theta = \pi/2$, corresponding to radiation normal to the magnetic field vector.

On adopting the numerical value $J_\nu = 10^{9.1}$ and considering in turn cases (a) to (d), we obtain the estimates: (a) $f(\gamma_0) = 10^{29.4}$; (b) $f(\gamma_0) = 10^{28.9}$; (c) $f(\gamma_0) = 10^{30.0}$; (d) $f(\gamma_0) = 10^{29.5}$.

Using the above estimates of $f(\gamma_0)$, we may estimate the energy U_0 (erg) of electrons responsible for the observed microwave radiation by the approximate formula

$$U_0 = 10^{-6.1} f(\gamma_0)(\gamma_0 - 1)^2 . \qquad (2.20)$$

We find that: (a) $U_0 = 10^{24.5}$; (b) $U_0 = 10^{22.7}$; (c) $U_0 = 10^{25.1}$; (d) $U_0 = 10^{23.1}$. We note that these estimates are of order 10^{-4} times the estimates of energy associated with elementary bursts.

We now consider the possibility that the electrons responsible for the observed microwave radiation are part of a power-law spectrum. We adopt Petrosian's model (P.30) for $f(\gamma)$,

$$f(\gamma) = C\left(1 + \frac{\gamma - 1}{\varepsilon_c}\right)^{-\delta} , \qquad (2.21)$$

where $\gamma - 1 = \varepsilon_c$ is the lower limit of the spectrum. The total electron energy is now given by

$$U_T = 10^{-6.1}(\delta - 1)^{-1}(\delta - 2)^{-1} C \varepsilon_c^2 . \qquad (2.22)$$

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This may be expressed alternatively as

$$U_T = (\delta - 1)^{-1}(\delta - 2)^{-1} \, \epsilon_c^2 \left(1 + \frac{\gamma_0 - 1}{\epsilon_c}\right) U_0 \quad . \tag{2.23}$$

On adopting the value $\epsilon_c = 0.04$, corresponding to a cutoff energy of 20 keV, we find that: (a) $U_T = 10^{27.5}$; (b) $U_T = 10^{23.8}$; (c) $U_T = 10^{30.8}$; (d) $U_T = 10^{25.6}$. It is clear that the estimates of total energy are very sensitive to the assumed values of δ and B, ranging from values much less than 10^{27} to values much more than 10^{27}. Since the "sub-bursts" detected by Kaufmann come from small flares as well as from large flares, it is more likely that the energy responsible for each such burst is produced by conditions (b) or (d), rather than by conditions (a) or (c). Hence it seems likely that the radiation comes from magnetic-field regions of order 10^3 gauss.

If the microwave bursts and the hard X-ray bursts were due to essentially the same energy-release process, one would expect that energy estimates would be similar, observed time durations would be similar, and that there should be a good correlation between the time curves of the two types of radiation. Recent studies by Takakura et al. (1983) have shown that the time curves at various microwave frequencies and at hard X-rays exhibit little correlation on time-scales of seconds, except when fast quasi-periodicity is evident, in which case the periodicity appears at all frequencies, possibly indicating that the same energy-release process is at work. In their analysis of other flares, Marsh et al. (1981) and Tandberg-Hanssen et al. (1983) have inferred that the population of energetic electrons that produce the impulsive microwave emission is distinct from the population of electrons that produce the hard X-ray burst.

If the energy-release process responsible for hard X-ray elementary bursts is taken to be the reconnection of an elementary flux tube, one must

look for a process smaller in scale to explain the microwave sub-bursts. For the dimensions, field strength and electron density assumed earlier in this section as being typical of an elementary flux tube, the Alfvén speed is $10^{8.5}$ cm s^{-1}. Hence a microwave sub-burst of duration only 10^{-1} s must originate in an energy-release process extending over no more than $10^{7.5}$ cm.

Although there is a great deal of uncertainty about the energy requirements for the microwave sub-bursts, it seems most likely that the energy is substantially less than that associated with the elementary X-ray bursts due to their greater frequency and shorter time scale. If we are correct in attributing elementary bursts to reconnection of individual flux tubes, then microwave sub-bursts must be explained in terms of energy release processes smaller in scale than elementary flux tubes.

Recent developments in reconnection theory indicate one way in which this requirement may be met. In an attempt to understand sudden current disruptions in tokamak devices, the reconnection ("tearing") process has been studied by computer simulation (Carreras et al. 1980), and by nonlinear analytical analysis (Carreras et al. 1981). It is found that if reconnection leads to the development of a single tearing mode, or to modes which do not interact with each other, then reconnection proceeds in two phases: (I) The initial phase described by FKR (Furth et al. 1963) linear theory, in which there is a slow but exponential growth, followed by (II) a nonlinear development in which the amplitude grows linearly with time.

If two or more modes are unstable and begin to grow, they will proceed through the above two stages and, if the spatial locations of these two modes are sufficiently close together, they will enter a third stage (III) in which the "islands" which develop in each mode come into contact. When this occurs, the interaction of the two modes leads to a very rapid exponential growth of

one or more modes, the rate of growth at this stage being considerably larger than the rate of growth in the initial regime of linearized theory.

In the cases investigated by numerical simulation by Carreras et al. (1980), the initial growth did, in fact, occur at a rate consistent with FKR theory, i.e., at a rate which is approximately the geometrical mean of the MHD rate and the diffusion rate. On the other hand, when mode-interaction occurred leading to the third stage of growth, the rate was closer to the MHD rate and, therefore, substantially faster than the FKR rate. If a similar distinction were to occur in the reconnection processes occurring in solar flares, it is likely that the difference in the growth rates between phases (I) and (III) would be much more pronounced, since the magnetic Reynolds numbers are much larger in solar flares than in laboratory devices due to the fact that the length scales are so much larger.

An important aspect of the third stage of the reconnection process is that the magnetic-field behavior becomes stochastic. Depending on the time scale, this may contribute to the rapid fluctuation in energy release during the impulsive phase of a flare. During the rapid mode of energy release (III), components of the electric field parallel to the magnetic field attain higher values, which could explain the acceleration of electrons to many tens of keV during the impulsive phase. Furthermore, strong MHD turbulence is developed, which can help explain the acceleration of electrons and ions to relativistic energies via stochastic acceleration.

The numerical simulations show that, during the third stochastic stage, the reconnection process develops substructure (magnetic islands) of which the transverse dimension is of order 0.1 R, where R is the minor radius of the magnetic-field configuration. In the analysis of Carreras et al. (1980) and Carreras et al. (1981), variations in the reconnection process along the length of the flux tube are suppressed so that these analyses yield no

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information concerning the longitudinal length scale. However, the analyses show that, in the rapid-growth phase, perturbations are propagating in the transverse direction approximately at the Alfvén speed. Since the Alfvén speed is a maximum rate at which perturbations can propagate in the longitudinal direction, it seems reasonable to assume that the extent of magnetic islands in the longitudinal direction is similar to that in the transverse direction, indicating that the longitudinal dimension also will be of order 0.1 R. If we consider, for definiteness, that $B = 10^2$, then $R = 10^8$ for elementary flux tubes of total flux $10^{18.4}$ Mx. Hence the dimensions of the magnetic islands will be of order 10^7 cm so that, if the free energy is about 10 percent of the total magnetic energy, the energy released per island will be of order 10^{23} erg. On comparing this estimate with our estimates of U_0 and U_T, we see that the "magnetic island" hypothesis can more easily be reconciled with estimates of U_0 than with estimates of U_T. If $n = 10^{9.5}$, the Alfvén speed is $v_A = 10^{8.5}$ so that the characteristic time scale for the development and decay of a magnetic island is of order $10^{-1.5}$ s. This is somewhat short compared with the time scales of the majority of microwave sub-bursts. Hence the length scale of magnetic islands in the solar-flare situation may be somewhat larger than 0.1 R, so increasing the time scale and considerably increasing the amount of energy released. For instance, islands with a characteristic scale of 0.3 R will have a characteristic time scale of 10^{-1} s and a characteristic energy release of order $10^{24.5}$ erg.

The above energy estimate agrees very well with our estimates of U_0 for the case $\delta = 3$, $B = 10^2$, and is comparable with our estimates of U_T for the cases $\delta = 3$, $B = 10^3$ and $\delta = 5$, $B = 10^3$. However, it is still small compared with the estimate we obtained for $\delta = 3$, $B = 10^2$. It is possible that the inferred power-law spectrum for electrons accelerated in solar flares applies

only to the average spectrum, and that the spectrum produced by an individual magnetic island is sharply peaked at an energy much higher than 20 keV. If this is the case, and if we interpret microwave sub-bursts as being due to individual magnetic islands, we can understand the general lack of correlation between fluctuations observed at different microwave frequencies and in X-rays.

3. Onset Phase and Late Phase (The Gradual Phases)

We pointed out, in the introduction, that the impulsive phase of a solar flare is typically preceded by an "onset phase" which involves soft X-ray emission (sometimes attributed to "preheating") and filament activation.

Soft X-ray emission and H-alpha emission typically persist for some time after the impulsive phase has ended. In some cases, this may be attributed to the hot flare plasma produced by evaporation during the impulsive phase. However, in other cases, detailed analysis indicates that continued energy release is required to explain this phase (Moore et al. 1980), showing that some flares involve a "late phase of energy release" (Sturrock 1980).

We refer to the onset phase and to the late phase of energy release as the "gradual phases", since they are similar and differ markedly from the impulsive phase. By comparison with the impulsive phase, energy release is slow, steady, and does not lead to acceleration of particles to high energies. On comparing the properties of the gradual phases with the various possible stages of reconnection discussed by Carreras et al. (1980) and Carreras et al. (1981), it seems likely that the gradual phases involve only the steady modes of reconnection (I and II), not the rapid stochastic phase (III) which is evident in the impulsive phase.

Even if the onset phase and the impulsive phase involve the same magnetic-field configuration, the transition from a slow state of reconnection

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to the rapid stochastic phase is not unreasonable. However, it is not so easy to understand why the stochastic phase should give way to the slow quiet mode, unless the late phase involves a different magnetic-field configuration.

In attempting to understand the processes responsible for the onset and late phases, we restrict our attention to two-ribbon flares which typically involve all three phases of energy release. Two-ribbon flares typically involve filament eruptions, and we follow Kiepenheuer (1964) in regarding the filament eruption and the flare as a single complex process. We therefore attempt to interpret the onset phase and the late phase by considering the role of the filament in the eruption-flare process.

Moore and LaBonte (1980), in their analysis of the filament eruption and 3B flare of July 29, 1973, state that "the eruption of the filament and the onset of the two-ribbon H-alpha flare were preceded by precursor activity in the form of small H-alpha brightenings and a mass motion along the neutral line and well below the bottom edge of the filament," and that "the onset of the flare ribbons occurred simultaneously with the filament eruption." In this, as in other cases, the beginning of the impulsive phase of the flare coincides with the beginning of the rapid vertical motion of the filament. Moore and LaBonte conclude that "both the destabilization of the filament and the initial flare ribbons resulted from magnetic-field reconnection below the filament; this initial reconnection triggered the flare."

In order to understand the interplay between filament eruptions and flares, it is necessary to have a model of the structure of filaments. The models proposed by Kippenhahn and Schluetter (1957) and by Kuperus and Raadu (1974) do not provide the complexity necessary to understand observations such as those of Moore and LaBonte (1980). Our proposal is that the magnetic-field structure of the filament involves a large number of flux tubes braided like a rope, extending along the magnetic-field reversal line, and with multiple

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connections on either side of that line (see Figure 2). We may then interpret simultaneous eruption of the filament and initiation of the flare as being caused by reconnection of contiguous but oppositely directed flux tubes linking the filament to the photosphere, as indicated in Figure 2. This reconnection has two effects: one is to produce flare-like brightenings of the footpoints nearest to the site of reconnection (and possibly other footpoints where the relevant field lines re-enter the photosphere), and the other is to partially disconnect the filament from the photosphere. As a result of this disconnection, the balance of forces will be changed and the filament will begin to move vertically upwards. This picture offers an explanation of the fact that the beginning of rapid eruption is coincident with initial H-alpha brightenings below the filament (Moore and LaBonte 1980; Moore et al. 1982). A combined filament eruption plus flare would occur if the initial reconnection triggered a runaway process of filament motion plus extensive reconnection.

Many filament eruptions do not involve flares. Hence reconnection cannot play an important part in such events. It is possible that, in such cases, the filament is anchored only at its ends and that the eruption is due simply to an MHD instability. Alternatively, it is possible that reconnection occurs, but only in those limited low-lying regions between adjacent footpoints (producing small H-alpha brightenings), and does not trigger reconnection of an extended system of flux-tubes, such as is required to produce a flare.

We now turn to the late phase of energy release of tworibbon flares, which is evident both from the slow separation of the the flare filaments and the slow energy release required to explain the detailed development of soft X-ray emission from such flares. The slow separation of the flare ribbons and

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the "rising mound" appearance of limb flares as observed in H-alpha (Bruzek 1964) can be explained very plausibly in terms of the progressive reconnection of an open magnetic-field structure (Sturrock 1968; Kopp and Pneuman 1976). However, if this structure were (as originally proposed) the preflare magnetic-field structure, then the vertical current sheet would be located above the filament so that, as noted by Svestka (1976), it is then difficult to understand that the initial flare brightenings occur below the filament and very close to the field-reversal line. However, the eruption of the filament leads to a stretching of the overlying magnetic-field lines. In this process, an extensive vertical current sheet is formed below the erupting filament (Figure 3). The late phase of a flare can now be understood as steady reconnection of this current sheet.

We have noted that the onset phase and the late phase differ from the impulsive phase in being comparatively slow and steady and in producing only low-energy electrons, as is evident from the X-ray spectrum. In the case of the onset phase, this difference may be due to the fact that reconnection is occurring very low in the solar atmosphere so that the plasma density will be high and the Alfvén speed correspondingly low. In the case of the late phase, the difference may be due to the fact that the newly formed current sheet is fairly smooth in structure rather than dominated by the current system of elementary flux tubes. However, these are merely suggestions: we need to learn more about the conditions which lead to either steady reconnection or stochastic reconnection in solar active regions.

Many flares appear not to involve a filament eruption. It is possible that some such flares do not involve the eruption of a magnetic-field structure or a similar MHD process. It is also possible that, in some such flares, such an eruption does occur but it is not visible in H-alpha because the configuration does not provide a support mechanism for cool gas or has not

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yet collected a detectable amount of cool gas. Zirin (1982) has, in fact, expressed the opinion that in almost all flares one can, with sufficient sensitivity, detect the presence before the flare of an elevated dark feature that vanishes in the course of the flare.

4. Discussion

The basic proposals advanced in this article are the following:

(a) the fine structure of the impulsive phase of flares may be attributed to the fact that the magnetic field is composed of elementary flux tubes,

(b) an elementary flare burst represents energy release of a single flux tube,

(c) the sub-bursts are due to the deveopment of magnetic islands,

(d) the onset phase of a two-ribbon flare is due to reconnection of contiguous but oppositely directed magnetic flux tubes linking the filament to the photosphere, and

(e) the late phase of a flare is due to reconnection of a current sheet formed by the filament eruption.

A number of topics require further theoretical study. These include the following: the structure of elementary flux tubes and their aggregations; energy release in single tubes and in aggregates of tubes; the structure of filaments and modes of eruption with or without reconnection; and consequences, such as acceleration, of the different modes of reconnection.

The further study of these proposals would be greatly advanced by certain observations. These include: the fine structure of the photospheric magnetic field and its relation to flare emission when a flare occurs. (Such observations could best be made by means of the Solar Optical Telescope.) The horizontal velocity field of active regions and the relation of photospheric

vorticity to flares. (Such observations could probably best be made by means of correlation techniques applied to sequential photographs of the photosphere.) The fine structure of filaments, aimed especially at determining the magnetic structure and the photospheric connection. (This would perhaps best be achieved by high-resolution study of the velocity field of cool gas in filaments.)

The proposals advanced in this article may, if substantiated, have useful implications concerning the problem of flare prediction. The energy released during the impulsive phase is due to the twisting of elementary flux tubes such as would be produced by photospheric vorticity. Hence the monitoring of the photospheric velocity field could give information which would help one to predict whether a flare with an intense impulsive phase were likely to occur.

If our interpretation of the mechanism of two-ribbon flares is correct, then the prediction of such flares involves first the prediction of filament eruption; second, the determination of whether or not this eruption involves reconnection or will trigger reconnection; and determination of whether the current sheet which would be produced by the filament eruption is likely to reconnect.

If Zirin is correct in claiming that all flares involve erupting dark features, then the prediction of flare occurrence will require intensive study of the structure and behavior of such features.

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Figure Captions

Figure 1 Schematic representation of possible coronal magnetic field structure, determined by the aggregation of photospheric magnetic field into discrete knots.

Figure 2 Schematic representation of possible magnetic field configuration of a filament.

Figure 3 Schematic representation of the development of an extended current sheet beneath an erupting filament.
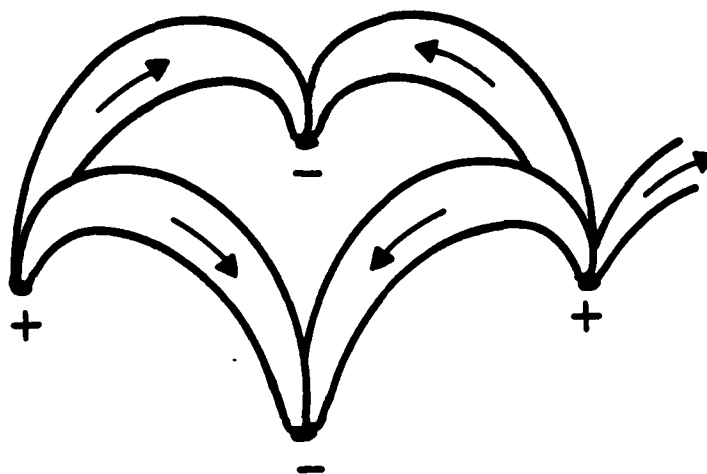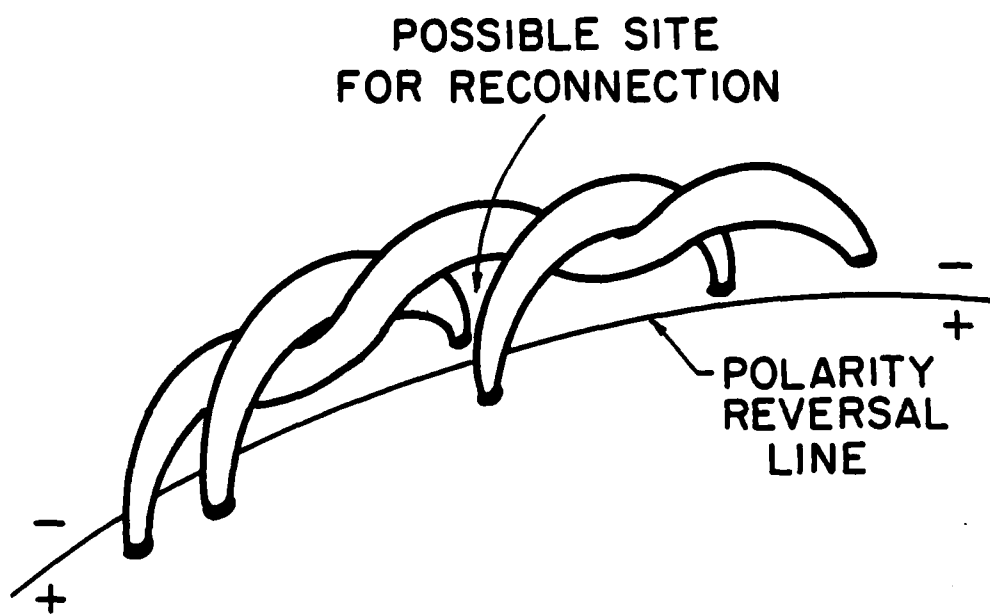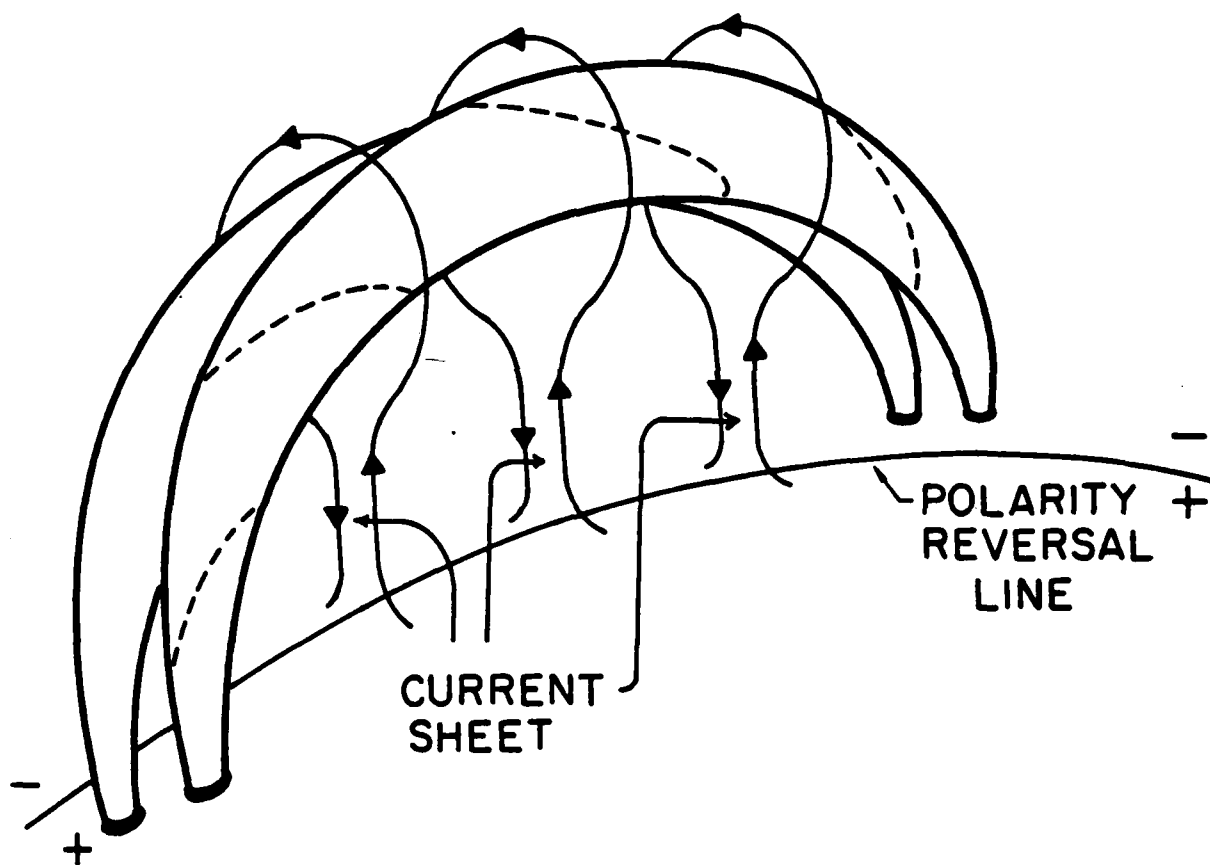
Figure 1

Figure 2

POLARITY REVERSAL LINE

CURRENT SHEET

Figure 3

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